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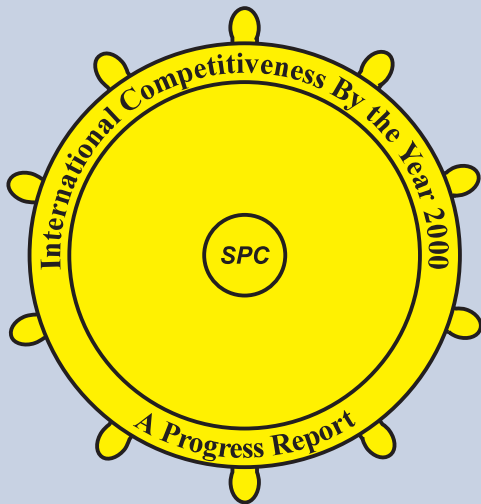
### **Paper No. 21: A Parametric Approach To Machinery Unitization In Shipbuilding**

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# A Parametric Approach To Machinery Unitization In Shipbuilding

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## ABSTRACT

*During the past ten years, both U.S. and foreign shipyards have developed advanced unitization concepts that include multi-level assemblies representing large vertical segments of ship machinery spaces. This paper describes a parametrically derived family of large, fully integrated standard machinery units that are applicable over a range of ship types and installed horsepower. The results include a hierarchy of standard units, the selection of standard unit sizes and interfaces, the development of parametric standards for system design, engine room arrangement and structural design, and machinery unit structural and outfitting design. Benchmarking is reported with respect to Japanese and European shipbuilding practices, and with respect to U.S. land-based industrial plant design and construction practices. The proposed unitization concept is demonstrated in a ship-specific engine room arrangement design effort. A business assessment for this unitization concept is presented which addresses its potential shipbuilding cost and schedule impacts as evaluated by three U.S. shipyards.*

## NOMENCLATURE

**Advanced Outfit.** Installation of outfit systems and components on a structural block or outfit unit prior to shipboard erection.

**Block.** Hull structural interim product which can be erected as a block or combined as a grand block.

**ERAM.** Engine Room Arrangement Model Project, part of the Navy's Mid-Term Sealift Technology Development Program.

**Grand Block.** Assembly of two or more structural blocks mated prior to onboard erection.

**Ground Outfit.** Outfit installation during on-unit and on-block outfit stages.

**Grand Unit.** Assembly of two or more outfit units mated prior to onboard erection.

**Integrated Machinery Unit.** Ship specific assembly consisting of one or several outfit systems including all mechanical and electrical components and subsystems in an area.

**On-Block Outfit.** Outfit installation on a structural block prior to erection onboard.

**On-Unit Outfit.** Outfit assembly and installation on an outfit unit prior to erection onboard.

**Onboard Outfit.** Outfit installation following structural block erection.

**Pipe Unit.** Assembly consisting of all pipe and adjacent distributed systems supported on a common hanger system.

**Standard Machinery Unit.** Assembly consisting of a standard structural unit, one or more system units, and all ship's distributed systems in an area. The standard machinery unit de-

sign is based upon standard unit structural and system interfaces.

**Standard Structural Unit.** Structural foundation and grating support for a standard machinery unit. The structural unit consists of a standard repeating structural pattern and contains framing and supports for system units and ship's distributed systems.

**Structural Unit.** Structural foundation and grating support for an outfit unit.

**System Unit.** Assembly consisting of all mechanical and electrical components making up a single subsystem on a common foundation.

## INTRODUCTION

During the past two decades, U.S. shipbuilders have applied advanced outfitting techniques to ship and machinery space construction in order to achieve reductions in production cost and cycle time. While the initial application was in on-block outfit of structural blocks, this soon evolved to include on-unit outfit using system and pipe units. Even in the most successful of these initial applications, shipbuilders found that significant onboard outfit installation and test remained in complex areas such as machinery spaces.

In 1992, National Steel and Shipbuilding Company (NASSCO) implemented an innovative machinery unitization strategy on its new construction Strategic Sealift Ships that resulted in the majority of machinery space equipment, components and systems being assembled in fifteen large integrated machinery units. These ships are currently in production with significant

reductions in cost and cycle time being realized. During the development of this application, the team recognized that significant non-recurring engineering and planning were required to support implementation.

In 1995, based upon this machinery unitization experience and knowledge of foreign shipbuilding developments during the 1970's and 1980's, NASSCO management developed the concept of a Standard Machinery Unit. This approach was based upon the standardization of system architecture and engine room arrangements, as well as the use of standard unit structural and system interfaces that would be applicable across a wide range of ship types and main engine horsepower.

The development of this concept and its application to a specific ship design will be described herein.

## DEVELOPMENT APPROACH

In early 1996, NASSCO was awarded a subcontract to further develop the Standard Machinery Unit concept as part of the ERAM portion of the Navy's Mid-Term Sealift Technology Development Program. To support this development, a standard machinery unit project team was assembled including personnel from engineering, manufacturing engineering, planning, production, materials, and cost engineering. The project team was supported by both internal and ERAM Project Steering Committees.

The technical development of the project focused on commercial ship machinery spaces using slow speed diesel power plants ranging from 10,000 to 50,000 BHP. Parametric analysis was used to systematically evaluate the key product variables and to select a single or family of similar solutions as appropriate. The key parameters or product variables considered included:

- Ship type
- Ship size and speed
- Engine room location
- Main engine vendor
- Main engine horsepower
- Owner options

A critical part of the development process included benchmarking of state-of-the-art marine and U.S. land-based industrial plant design and construction practices as described below.

## BENCHMARKING

The team benchmarked "World Class" land-based and shipbuilding practices in order to evaluate the potential for applying advanced unitization concepts to shipbuilding. The unitization approaches observed in each case were customized to the fabricator's or builder's individual requirements. A prevalent strategy in land-based applications was to complete the majority of fabrication in the central production facility thus minimizing the need for a large work force and support facility onsite in a remote or rugged location. In shipbuilding applications, the primary driving force for unitization was concurrent construction of the ship's hull and the machinery systems.

### Shipbuilding Applications

The first step of the shipbuilding benchmarking effort was to identify ship construction facilities presently applying advanced

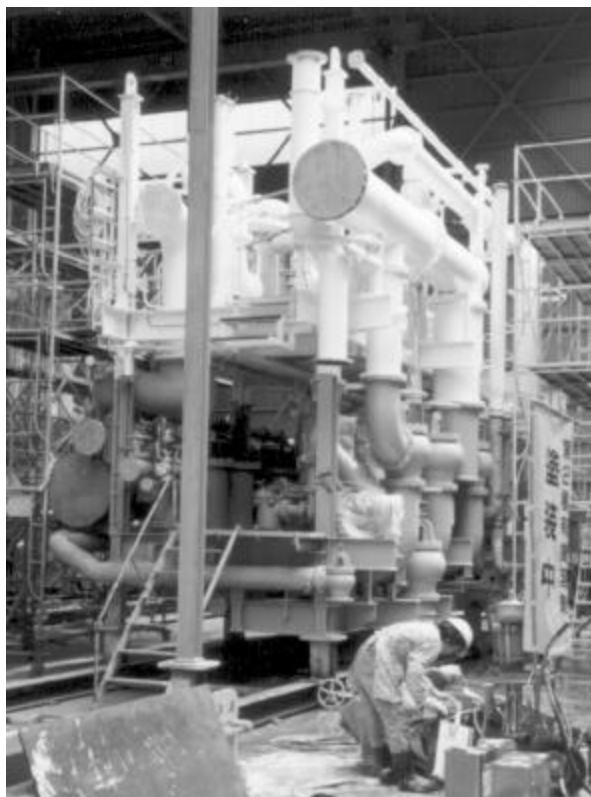


Fig. 1 Grand Unit at IHI's Aioi Facility

unitization concepts. Conventional shipbuilding practices were also reviewed to best evaluate the advantages and disadvantages of unitization.

Ishikawajima-Harima Heavy Industries (I.H.I.), of Japan, has been building merchant ships since 1990 using a unitization concept employing standard machinery units. These units are fabricated at the Aioi Works, joined into a grand unit, as shown in Fig. 1, and then barged to their Kure facility for shipboard erection. The grand unit is installed along the forward engine room bulkhead immediately forward of the main engine.

IHI uses parametric design in that a large percentage of the modules are reused from ship to ship with some minor modification. Both their system design and detail design start with a "base standard" which is then modified as needed.

Another shipbuilder who makes use of large standard machinery units is Thyssen Nordsewerke, of Germany. To date they have applied their version of unitization to slow speed diesel container ships in the 16,000 KW power range. However, they believe that the same arrangement can be applied up to approximately 20,000 KW. The original ship design was not developed to incorporate unitization, therefore the full benefit of the concept was not realized.

It appeared that Thyssen did not use parametric design for their unitization program, but rather employed a custom design process. However, Thyssen stated they are moving toward standardization with the intent of developing a generic set of machinery units. The unit structure and ship's hull structure of the design were designed completely independent of each other.

Additionally, the team evaluated current practices in their

own yard. NASSCO has been constructing large integrated machinery units for all ship contracts since 1986. Most recently, the Sealift New Construction Program has made maximum use of integrated machinery units. Fig. 2 shows a lower-level seawater cooling unit. An entire set of lower engine room units were built side by side, completely outfitted, and then erected onboard and bolted together. These units, however, are ship specific and cannot be reused from one ship class to the next.



Fig. 2 NASSCO SLNC Lower-Level Seawater Unit

The team also investigated the practices of Kawasaki Heavy Industries (KHI) of Japan. KHI does not utilize unitization to the extent that this study proposes but they do make use of what is referred to as system units. The system units incorporate the concept of standard system design at the design level, but not at the production level. They do not unitize at the production level for the following reason: The additional steel required for unitization increases material cost, adds weight, and decreases fuel efficiency. However, KHI does envision that standard machinery units provide the following advantages:

- Reduced overall production cost
- Reduced system and detail design cost

#### Land-Based Industrial Plant Design and Construction Practices

The team visited two facilities assembled using unitized construction techniques. Research focused on the design and construction practices of one company, Raytheon Engineers and Constructors. Additionally, the team visited the company's engineering and fabrication facility.

**Design.** For each new project a team is assembled comprised of the customer, multi-discipline engineers, constructors and fabricators. The team conducts a multi-level review and development process. Concurrent engineering and design occurs throughout these levels, beginning with process sizing, major equipment sizing, and plant layout to satisfy process and unitization needs. Detail design takes place at later stages of development.

Guided by a set of "expert rules" the units are parametrically designed based on plant size and several other considerations including:

- Equipment arrangement requirements
  - Process requirements
  - Fabrication technique requirements
  - Lifting or rigging requirements
  - Transportation requirements
- Land-based industrial plant and standard machinery units are

comprised of two groups: *process specific units*, which are built custom for each specific application, and *utility/support units* which are standard. The ratio between the quantity of custom and standard units varies significantly based on the type of project.

Industry standards are used during the design phase, but often vary based on national and local codes, customer requirements, design requirements, and economics. These industry standards are generic, and are not developed specifically for design and fabrication of machinery units. Upon completion of each machinery unit design, the completed drawings are placed in a library for possible use on future projects.

Fully outfitted machinery units typically consist of the following: a structural sub-base or foundation, machinery and electrical equipment, ventilation ducting, free standing tanks, equipment removal gear, associated piping, wireways, cable, and walking surfaces. Machinery units may incorporate the walls and ceiling of the associated building or structure. Electrical systems are incorporated into the unit design with full pre-wiring of all circuits, except on those systems designated as uninterruptable by code. Electrical connectors are used between units in lieu of hard-wiring. Cold checks are performed at the unit outfit stage. Control rooms are designed and fabricated as fully outfitted machinery units. Storerooms, offices and other commercial type spaces are usually procured as units from specialty vendors.

Transportation to the erection site varies based on geographical location, and local restrictions. Alternate forms of transportation include truck, rail, and barge. All three methods are suitable for transport of units designed for shipboard application.

**Construction.** The assembly execution plan pre-designates staging assembly areas. Steel is fully erected up to the top elevation which is left open for equipment and piping erection. Wide flange beams, channel, rectangular and square tubing are used in the fabrication of the unit structure. Selection is dictated by structural and economic requirements. Walkways are of diamond plate or open grating, bolted, welded or saddle clipped, made in pre-assembled galleries and installed on the unit. The unit structure is usually of welded construction accomplished in the shop, with bolted connections for field construction.

The construction process follows a logical sequence of steel assembly, paint, equipment installation, pipe assembly, instrumentation and electrical installation, and test. Units are usually assembled individually unless process or testing requirements require integration. Pipe make-up pieces between units are not necessary due to the close tolerances attainable using standard framing patterns, assembly jigs, and manual and electronic measuring devices.

#### Benchmarking Results

Benchmarking both shipbuilding and land-based construction and unitization practices revealed that the advantages of unitization far outweighed the disadvantages. Although the rationale for unitization varied slightly among the applications, the following advantages were manifest in both:

- Reduced overall construction schedule
- Faster activation of plant upon construction completion
- Reduced overall production cost
- Reduced system and detail design cost

- Improved quality and safety

## MACHINERY UNIT DESIGN STRATEGY

The design strategy employed by the team utilized parametric analysis to systematically evaluate the key product variables and select a single or family of similar solutions. The resulting parametric design guidelines were organized in the following six separate but related areas:

- Systems Design
- Arrangement Design
- Structural Unit Design
- Machinery Unit Design
- Engine Room Structural Design
- Build Strategy

The analysis and development of these guidelines is described in the following sections.

## SYSTEMS DESIGN

The rationale behind the parametric design for engine room systems is part of an ongoing effort to improve engineering, design and production techniques throughout the U.S. shipbuilding industry. The shipboard system designs described in this paper are meant to be representative of generic systems applicable to a broad category of ship types over a relatively large installed horsepower range. The objective behind this system design approach is twofold:

- First, the parametric system design selectively reduces the number of system components to the minimum required for safe and efficient operation of the vessel.

- Second, the concept focuses on identifying systems which are common to most types of vessels presently under consideration by worldwide ship owners and operators.

The selected systems are initially developed to suit a vessel of mid-range size and powering. By utilizing parametric design concepts, the componentry identified for these selected systems is sized accordingly for vessels of greater or lesser size and powering.

A comprehensive study of shipboard system diagrams from leading shipbuilding companies such as Kawasaki Heavy Industries (KHI), and leading engine manufacturers such as Burmeister and Wain (B&W), and Sulzer formed the basis for system design and componentry selection. Information regarding system design and component selection is incorporated into the standard system diagrams; consequently, these system diagrams are representative of current industry standards.

## Traditional Approach

Traditionally, US shipbuilders have considered the system design of each new vessel as an individual effort. This approach has required significant labor hours for the development of customized shipboard systems for each new design. The parametric design concept is a method by which this task can be minimized. The parametric design concept views each vessel as part of a larger effort inclusive of many different types and sizes of vessels, not as an individual effort.

The initial design of a standard system which is generic to a wide cross-section of vessel types and sizes may represent an increased effort over a single ship design. However, the long-range benefits of a common design are apparent in improved quality and

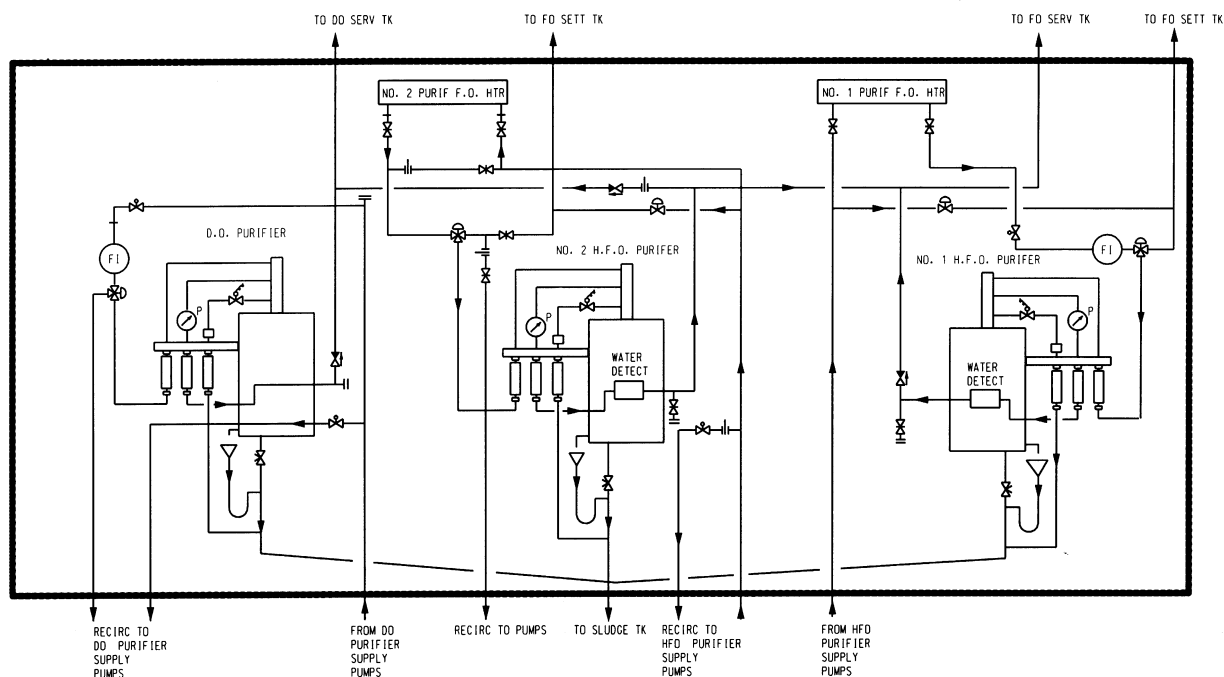


Fig. 3 Fuel Oil Purification System Unit Diagram



reduced engineering, design, and production costs over the span of several contracts. The parametric approach augments benefits derived from a standardized multiple ship approach. These advantages can be fully realized in construction of series-built standard designs or vessels of conventional features.

### Parametric Approach

To successfully implement a parametric design concept and compete in a global marketplace the U.S. shipbuilding industry must strive to accommodate customer needs. The concept introduced by this paper is unique in that it encompasses a majority of engine room systems. It is critical that both owners and shipbuilders agree on standard system architecture common to several vessel types and sizes. Although these selected systems must maintain a standard design, it is also important that the systems be flexible enough to accommodate customer unique requirements. The system designs suggested in this paper allow for such variations based on owner's desires.

Regarding the worldwide market for ship construction, the project focuses on five ship types: *Crude Oil Carriers, Product Carriers, Container Ships, RO/RO Vessels, and Bulk Carriers*. This decision was made in anticipation of the types of ships that may be ordered by the world market in the near future.

Integration of the parametric design concept first required identification of those systems that are common throughout this range of ship types. Data collection gained through investigation of previously constructed U.S. and foreign vessels provided the basis for a matrix identifying principle engine room systems. The relationship of these systems to various ship types was determined with regard to pertinent characteristics.

### System Selection

From this matrix 23 systems were selected for further development based on their commonality across multiple ship types. Standard system diagrams were developed for these systems.

The major equipment of the selected systems was then compared to ships previously constructed to consider possibilities for componentry reduction and simplification of system architecture. The major components of these systems were then arranged into individual system units based on a mid-size vessel. The team developed a second matrix to identify the relationships between the units and the principle engine room systems. Individual system unit diagrams were created depicting major componentry and the associated system piping. A representative sample of these diagrams is presented as Fig. 3.

### Distributive Electrical Systems

The team determined that by using a distributive system architecture for electrical power and automation, system cable footage and routing was simplified. Using this type of architecture, large electrical components such as: group controllers, power panels, and data acquisition units were systematically distributed throughout the engine room. This approach provided an increased level of local control and remote alarm monitoring, reduced cabling requirements, and increased pre-outfit potential when compared to a centralized system.

### System Unit Selection

A representative sample of six principle units were selected for further development and component selection. These six units were:

- Fuel Oil, Diesel Oil and Lube Oil Fill and Transfer Unit
- Main Engine and Diesel Generator Fuel Oil Heating and Service Unit
- Fuel Oil Purification Unit
- Lube Oil Purification Unit
- Fresh Water Generation Unit
- Fresh Water Transfer and Potable Water Unit

Initial equipment selection for these units was performed using a mid-size vessel as the model. The design team determined that natural size/model break points generally do not exist for component selection throughout the size and horsepower ranges for these vessels. Through analysis it was decided that a division of three equal groups would be sufficient to size equipment for most major systems.

These three divisions were based on main engine horsepower, crew size, or cargo requirements, depending on the function of the respective system. Twenty main engines were selected from two major engine manufacturers (B&W and Sulzer). Selection of these engines, covering the horsepower range from 10,000 Hp to 50,000 Hp, was prerequisite to auxiliary component selection.

### Equipment Selection

Prior to equipment selection, vendor information on major components was evaluated and a library was created to ensure that only currently manufactured components would be selected.

Equipment and componentry was selected using generally accepted system design guidelines. In all cases, equipment was selected from standard models of two or more manufacturers. Ideally, in practice manufacturers' components would be pre-approved by the shipyard and registered as "standard equipment" to facilitate the selection process. The associated components were then scaled up or down to accommodate the parametric sizing of the system units.

### Intended Use

The system units developed for this paper define the connectivity requirements between principle systems. The requirements of the system units also define an affinity for interrelated components and systems. The engine room arrangement templates and structural designs which follow are based on these system unit diagrams, and are systematically arranged to provide design efficiency.

### ARRANGEMENT DESIGN

The team's approach to arrangement design is meant to govern the final configuration of the engine room by controlling the parameters that influence design. With this approach, most high-level strategic decisions are made prior to the individual designers' commencement of arrangement design. Furthermore, the use of parametric methodology ensures that arrangement designs are not unique and that the same basic conceptual arrangement is em-

ployed throughout various ship types.

Several problems arise when using the traditional approach to engine room layout:

- Arrangement design for any given vessel is generally treated as unique. This increases design time and increases the possibility for design inconsistencies from vessel to vessel.
- Individual designers are responsible for both high-level and detail decisions regarding arrangement. As the designers and their expertise change, then so does the arrangement.
- Constraints imposed by structural scantlings often make it difficult to design an efficient arrangement. These constraints normally dictate the designers' flexibility with regard to arrangement. Designers must consider structure such as bulkheads and stanchions within the engine room space, and work around these obstacles.
- Distributive system routing, access requirements, and lifting requirements are often considered only as an after-thought due to the inherent complexity of equipment arrangement. This complexity is further amplified by imposed structural constraints. Late consideration of these important design factors often results in a less than efficient design.

### Parametric Approach

The parametric approach for engine room arrangement consists of decisions made on two distinct levels. High-level strategic decisions consider all variables in an attempt to reduce variation, and secondary decisions subsequently follow to minimize variation at the detail level.

Ideally, ships' lines and approximate engine room locations for a given vessel type are considered the primary fixed constraints for higher level analysis. This rule provides flexibility to determine an ideal engine room model for a given vessel type.

The goal of the team was to define a family of ideal models for engine room arrangements within the array of vessel types under consideration. An ideal engine room model requires an analysis of the relationship between major principle systems and the connectivity requirements of their distributive systems. The previously completed parametric analysis of systems provided a

powerful tool to define the necessary relationship between the major principle systems.

### Results Achieved

Five engine room arrangement templates were developed. Fig. 4 is a representative sample. These models are based on the five ship types previously selected, and the grouping of major systems resulting from the parametric analysis of systems. The templates represent ideal arrangements for engine rooms within the ship types under consideration. Although five very distinct templates were developed, one for each specific vessel type, it should be noted that all templates bare similarities to each other, based on the optimum location of major systems.

Most systems have requirements to be in a certain geographical area within the engine room in support of system functionality and efficiency. High-level decisions include: grouping all fuel and lube oil systems together, grouping all water cooled systems together, and keeping the Engineer's Operating Station close to the generators and as high in the engine room as possible. Such decisions reduce the requirements for distributive systems, and minimize interference of systems. Since the principle systems considered exist on most every ship type, the grouping of machinery units remains virtually unchanged.

Using templates as a basis for engine room arrangement provides the following benefits:

- Designers are provided high-level guidance. Such guidance leads to a common goal of efficiency in arrangement design.
- Engineering management, utilizing these templates, can incorporate and manage high-level decisions to control the outcome of the design process.
- The arrangement design is repeatable for a given vessel type and size, as well as for vessels of other types and sizes.
- Proper utilization of the templates will not only produce a highly efficient design, but will also reduce design time.
- Provides a common starting point for a concurrent engineering effort.

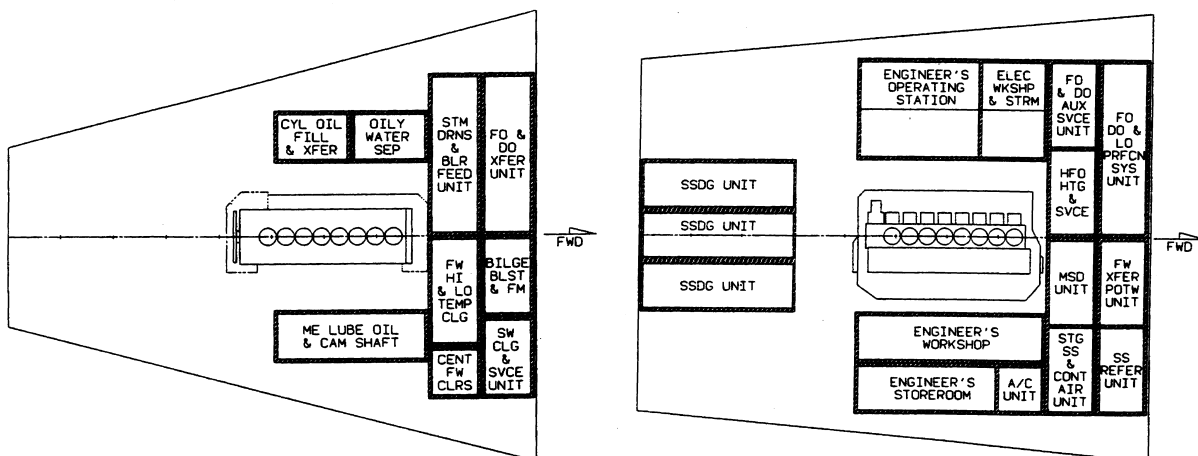


Fig. 4 Arrangement Template: Engine Room Aft, RO/RO with Low Head Room

## Intended Use

The templates outlined by this paper are intended to equip engineering managers with a powerful tool to quickly select an arrangement strategy and make initial design decisions. The templates also enable management to effectively communicate their decisions to design engineers with a high degree of confidence that progress can be controlled with minimum effort and re-direction.

Strategies for distributive systems and distributive system lanes can easily be outlined. Pipeways, electrical wireways, and vent runs can be identified, evaluated, and selected. In addition to distributive system routing, access, equipment removal, and lifting requirements can also be considered and identified at this stage. Experience has shown that early implementation of the above strategy will improve design efficiency will provide for reduced cost and schedule during production.

## STRUCTURAL UNIT DESIGN

The team developed a design strategy and guidelines for standard engine room structural units that can be used in a wide range of vessel types and sizes using a parametric approach. Engine room configuration using parametric design calls for a standard building block, which is defined as the structural unit.

Ideally, in order to remove the adverse effects of the engine room structure upon the framework of the structural units, it is necessary to uncouple the units from the main hull structure of the engine room. If this is not possible it is then necessary to include the effects of primary hull loads when designing structural units. The structural unit is built within the design parameters inherent to the internal structure of the unit, yet it still achieves the required effects on hull integrity and hull vibration.

## Standardized Approach

The design for standard structural units outlined in this paper results in similar structural arrangements and systems across ship types regardless of the selected design team and their individual expertise. Subsequently, this approach will produce a high-level of commonality, thereby reducing design cycle time and costs associated with construction. By virtue of a standardized approach, the structural unit design is based on two parameters which vary little from ship to ship. These parameters are *loading* and *vibration*. Key variables such as ship type, size, speed, horsepower, engine room location, and engine room size have minimal effect on the structural unit parameters.

A standard engine room is considered as a two or three level structure comprised of multiple units arranged on each level constructed around the main engine. The number of units comprising each level will be discussed later in this paper. Using the five templates as previously described, an analysis was performed. This analysis considered; the relative size of the system unit arrangement, the available area within the engine room (engine room volume), and shipping constraints (if the structural unit were to be constructed in a facility outside of the shipyard). The analysis included vessels of varying breadths, using Panamax beam of 32.2m (106 ft) as a break point for structural unit sizing. The team concluded that a standard structural unit of 3m (10 ft) wide by 3m

(10 ft) long by 3.6m (12 ft) high would be appropriate for all vessels below Panamax beam, while a standard structural unit of 3.6m (12 ft) wide by 3.6m (12 ft) long by 4m (13 ft) high would be required for vessels of Panamax beam and larger. A possible need for deviation from these standards was foreseen to accommodate SSDGs, large air receivers, or to conform to the main hull structure in certain areas of the engine room. In accordance with the five templates, these taller units would be located on the upper level so as not to interfere with units above.

## Loading Criteria

The loading criteria was determined by evaluating the weight and geometrical features of typical machinery units and equipment. For a standard structural unit, three distributed loading categories were selected. The structural unit strength and vibration adequacy were verified using structural engineering principles and Finite Element Analysis (FEA).

**Lower-Level Units.** Units designated for installation on the lower engine room levels are designed for system unit loads of 1220 Kg/m<sup>2</sup> (250 Lb/ft<sup>2</sup>). The girder members and grid members are designed for these loads and appropriate vibration levels. The vertical members are designed not only to support their own unit load but also to support the load transmitted from the levels above.

**Middle and Upper Level Units.** The mid and upper level units, which contain auxiliary machinery, are designed for a 1220 Kg/m<sup>2</sup> (250 Lb/ft<sup>2</sup>) loading. The upper level units used for store rooms and control rooms are designed for a 732 Kg/m<sup>2</sup> (150 Lb/ft<sup>2</sup>) loading. All units are designed for the appropriate vibration levels. The vertical members of these units are also designed to provide support for the load transmitted from the levels above.

**Upper Level Generator Units.** The upper level generator units are similar to the upper and mid-level auxiliary units in geometric configuration, but are designed for 2197 Kg/m<sup>2</sup> (450 Lb/ft<sup>2</sup>). This design reflects loading from SSDGs and air compressor sets located on this level. The component framing members are of similar shape of the earlier two unit types but are heavier sections.

## Vibration Criteria

In defining the vibration criteria, two sources of vibration excitation were considered: the propeller blade rate pulsation and the engine beat rate pulsation. In a vessel with an engine room aft configuration, the blade rate becomes the dominant limiting criteria. Conversely, in a vessel with an engine room located 2/3 aft, the energy content in blade rate pulsation is much lower and the engine beat rate becomes the dominant limiting criteria. The structural unit, as well as the multiple unit arrangements are designed to keep their natural frequency and even higher modal frequencies out of the frequency ranges of concern.

## Structural Unit Configuration

The template for an engine room 2/3 aft container ship was selected for detailed analysis, and three representative structural unit detail arrangements were developed. All three of these structural units have the same structural configuration, but vary in overall dimensions and component scantling sizes.

Regarding construction, the following two variations of the basic structural unit configurations were analyzed:

- Longitudinal system
- Transverse system

The team concluded that transverse grid members were preferable for support of piping runs. Vertical members are kept continuous and longitudinal load carrying members (girder members) are inter-coastal between adjacent units comprising a multiple unit arrangement.

The framing members, or scantlings, for these structural units are very much dependent on the characteristics of the standard machinery unit which it incorporates. The horizontal members of the structural units are designed as I-beams or W-sections as shown in the AISC Steel Construction Manual. The vertical members are designed as I-beams, except in areas requiring mechanical connection to adjacent units. For this application the vertical members are designed as channels thereby forming an I-beam when mechanically joined to an adjacent unit with similar channel construction.

In standard machinery unit applications, adjacent units are mechanically joined using bolted construction. The structural units are arranged such that the vertical I-beam stanchions of a unit land on the vertical stanchions of the unit below. Ends of the vertical members are capped with flat plate pieces to ensure proper alignment and facilitate mechanical fastening to vertical members of adjoining units. Horizontal orientation of units is accomplished in such a way as to allow channels of adjacent units to align back to back or to have their flanges side by side to allow for mechanical fastening.

## MACHINERY UNIT DESIGN

The machinery unit design arrangement selected by the team is based upon parametric analysis of the system designs, engine room arrangements, and structural unit design previously discussed. The integration of standard system units and selected individual components along with the ship's distributive systems onto standard structural unit building blocks creates the complete engine room arrangement. The use of parametric design strategies allows for standardization of such machinery units and their structural and system interfaces across the required range of ship types and sizes.

### Parametric Approach

Parametric analysis of the machinery unit design was based upon the analysis described in preceding sections. The arrangement selected included standard locations of system units, walkways, equipment removal routes and monorails, pipelines, cableways, and structural interfaces from unit to unit.

The team also performed structural unit size analysis for the arrangement of auxiliary system units, selected components, ship's distributed systems, and for machinery control and workshop spaces. The team's analysis concluded that standard structural units of 3m (10 ft) wide by 3.6m (12 ft) high are appropriate for

all vessels below Panamax size, while structural units of 3.6m (12 ft) wide by 4m (13 ft) high are recommended for larger vessels.

## System Unit Design

System unit design was based on analysis of the system unit diagrams previously developed. The analysis was performed to determine the optimum size and arrangement of each type of unit. System unit arrangement sketches were developed for nineteen system units based upon these arrangements and the connectivity requirements between the principle systems. 3-D system unit drawings were developed for the six systems identified in the system design section. A typical system unit is shown in Fig. 5.

The system unit designs include detail arrangements of the sub-bases, equipment, and systems incorporated on each system unit. The designs also include detail information on unit height and weight. Although not accomplished within the scope of the initial project, the long-term plan is to develop a family of parametrically

sized units that cover the total range of system capacity. Many system units such as purifier skids are available from equipment vendors. It is envisioned that the shipyard would design and build the balance.

## Standard Machinery Unit Design

The standard machinery design combines standard system units, selected individual components, ship's distributive systems, and a standard unit structural pattern to create a total engine room system that replaces conventional flats and distributed systems and components. The arrangement of typical machinery units was developed to test and evaluate the design concept. This evaluation considered the following: Human factors engineering, equipment maintenance and removal envelopes, simplified system routing and installation arrangements, standardized system unit locations, units to handle machinery control and workshop spaces, and standardized system interfaces from unit to unit. In certain cases such as the machinery control room, workshops, and store rooms, it is advantageous to use two machinery units, side by side, to form the space.

The arrangement of two standard machinery units forming

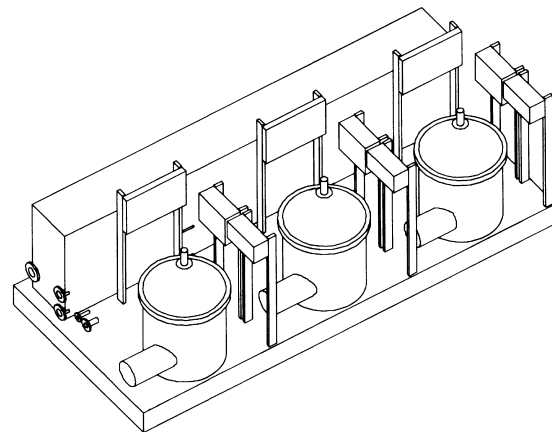


Fig. 5 Fuel Oil Purification System Unit

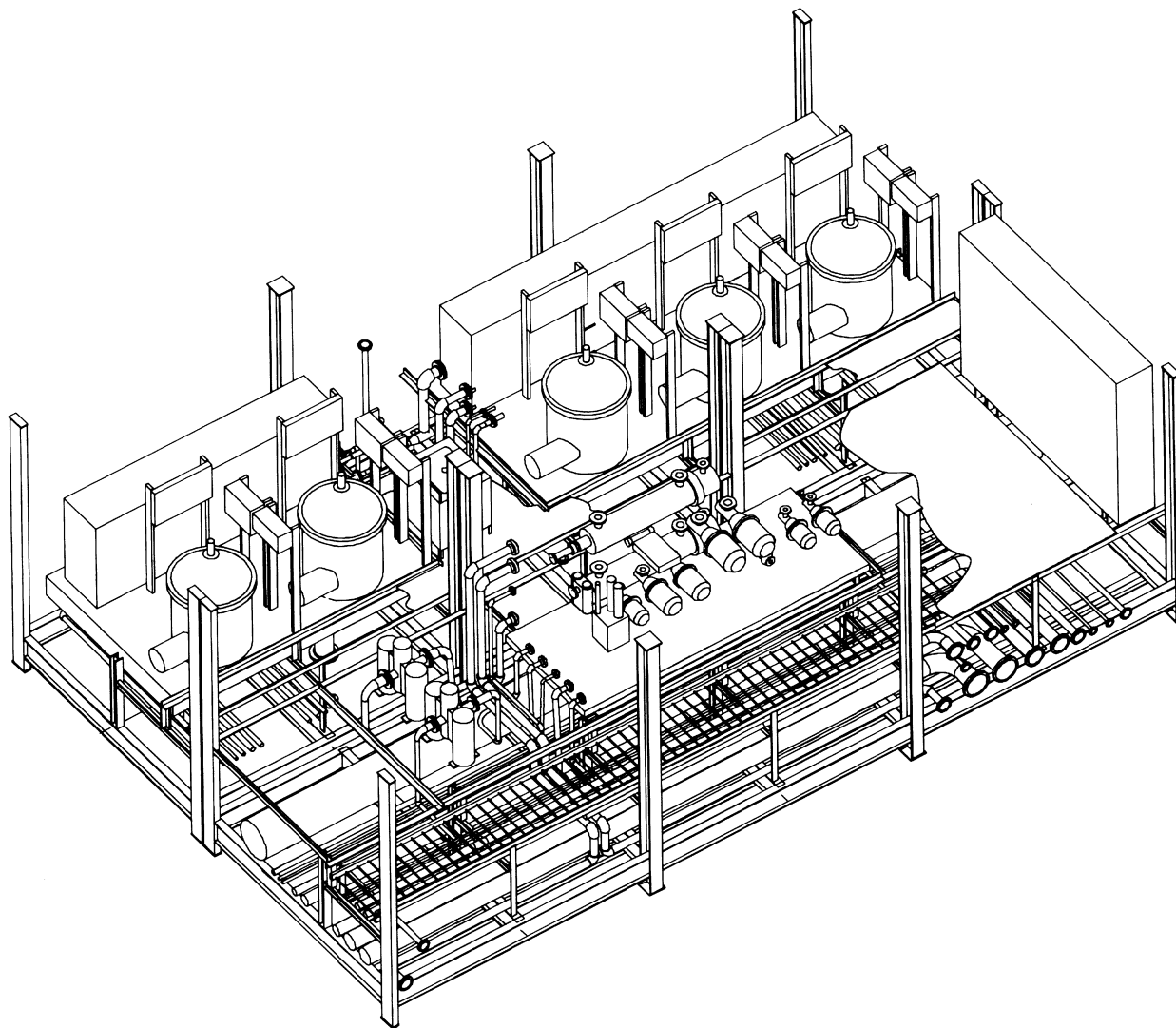


Fig. 6 Two Standard Machinery Units Containing LO, FO & DO Service & Purification System Units

the fuel and lube oil purification and service space is shown in Fig. 6. This figure shows the arrangement of system units, individual components, ship's distributive systems, and walkways within the machinery units.

Although not performed within the study, the long-term plan is to develop a complete library of standard machinery unit construction arrangements and details to support detail design. This would include the development of standard owner options such as modular bulkheads to support an enclosed purifier space.

### 45,000 BHP Baseline

Utilizing the system designs, system equipment, arrangement templates, structural units, and machinery unit designs previously described the design team performed an initial application of the standard machinery concept on a container ship with an engine room 2/3 aft. This design became known as the 45,000 BHP baseline, and it was key in working out and demonstrating many of the unit arrangement concepts.

### Results Achieved

The system and machinery unit design guidelines and their initial application to the 45,000 BHP baseline demonstrate the feasibility of the modular engine room approach. Additionally, the initial design application on the baseline arrangement validates the benefits of the parametric approach described in previous sections.

The team anticipates that the development of system and machinery unit design guidelines may represent an increase in initial design manhour costs when compared to a traditional design effort. However, the team also determined that the availability and use of these design guidelines will facilitate the rapid completion of the design process with a commensurate increase in design quality. The potential cost savings of such a library of standards over the span of several ship contracts was observed at the Japanese shipyards and industrial sights benchmarked as part of this study.

### ENGINE ROOM STRUCTURAL DESIGN

The development of parametric standards for engine room structural arrangement is required to ensure effective integration of unitized engine room structural units into the primary ship structure. As stated previously, the design of the engine room structural arrangement must be developed in such a way as to permit the uncoupling of the structural units from the main hull structure while achieving both hull and machinery system performance requirements. Important factors that must be considered are:

- Hull integrity
- Longitudinal strength
- Adequate stiffness and strength in way of main propulsion system installations
- Adequate and proper support for machinery system components and distributive systems within the engine room

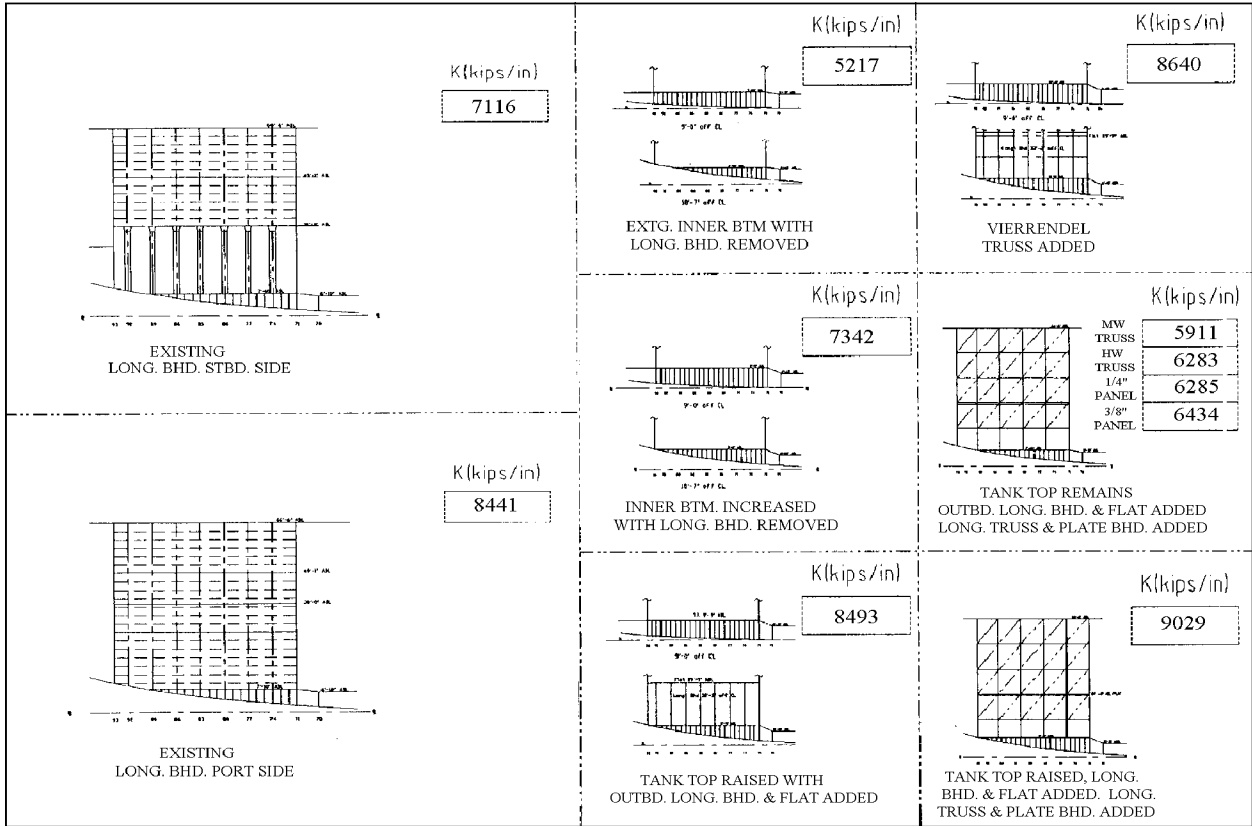


Fig. 7 Stiffness Comparison of Various Engine Room Structural Arrangements

- Proper support for superstructures that are located in way of the engine rooms and machinery space casings

A strategy was developed to compare alternative structural system concepts and to qualitatively establish target structural performance capabilities. This strategy was then implemented to select those approaches that were most cost effective, and that would enhance the development of optimum engine room structural units and a self supporting superstructure.

### Application of Parametric Approach

To account for the key variables previously identified, a parametric design approach was established to qualitatively and quantitatively assess and develop alternative engine room structural arrangements. These alternative candidates were further evaluated to select a proper standard for engine room structural arrangement. Baseline stiffness characterizations were established for existing ship designs in order to provide a basis for evaluation.

### Initial Concerns and Challenges

Issues of longitudinal strength and hull integrity were integral during the concept level of design development. In a traditional engine room structural arrangement double bottoms are supported by twin longitudinal bulkheads. These longitudinal bulkheads effectively reduce the span of the innerbottom in the transverse direction to 1/3 of its unsupported breadth. Thus the longitudinal bulkheads are an extremely important structural system component in providing adequate stiffness in way of main engine installations in the 2/3 aft engine room location. A challenge facing the team was to design an engine room structural arrangement to support standard machinery unit outfitting yet provide the required stiffness and strength.

A typical engine room structural arrangement employed in an engine room aft configuration utilizes similar innerbottom construction to that described for the 2/3 aft arrangement. However, the engine room aft arrangement usually does not have longitudinal bulkheads running down the length of the engine room. Generally, the engine room is narrower due to the inherent hull lines, and therefore the hull side shell, in a single shaft ship with a skeg, provides support for the innerbottom.

Alternative engine room structural systems that are more amenable to the unitized engine room design must achieve required stiffness characteristics in order to provide proper support to main engine and machinery within the engine room. Another challenge the team faced was to design an engine room structural system to allow the main engine foundations, unit structure, and superstructure to perform independently, or be self supporting, without negatively affecting each other.

### Hull Integrity and Longitudinal Strength

The alternative engine room structural arrangements developed to provide support to the main engine and machinery units do not retain the traditional longitudinal bulkhead structure. Traditional structure is depicted in Fig. 7. The port bulkhead extends fully from the bottom shell to the weather deck, while the starboard bulkhead is solid from 9.7m (31'-8") ABL to the weather deck with stanchions extending from the lower edge of the bulkhead down to the innerbottom.

### Alternative Engine Room Structural Arrangements

Five alternative engine room structural arrangements were evaluated against a traditional design to determine the optimum engine room structural arrangement to support unitization. Alternative arrangements considered include the following:

- Traditional design with longitudinal bulkhead removed
- Deepened innerbottom design with no bulkheads
- Deepened innerbottom design with longitudinal bulkheads
- Deepened innerbottom design supported by outboard longitudinal bulkheads and flat designed to reduce the effective width of innerbottom
- Deepened innerbottom design with no bulkheads and an expanded engine room length

### Validation of Alternative Arrangements

In order to validate the alternative engine room structural arrangements, the various configurations were modeled using FEA. First, more detailed plate models were constructed which characterized a typical prismatic shaped engine room of a Panamax containership. Three point loads were applied to the model located along the bottom longitudinal structure in line with the engine mounting bolts. Longitudinally, these loads were located at even intervals along the length of the engine room.

In order to quantify the stiffness of the engine room structural arrangement, an effective "k" value was calculated by dividing the sum of the vertical deflections of the structure at each of the applied loads by the sum of the applied loads. This "k" value is indicative of the vertical stiffness of the structural system and represents the relative ability of the system to match the vibrational resistance of the traditional configuration. Stiffness for the alternative configurations are provided in Fig. 7.

### Engine Room Structure and Machinery Unit Interfaces

To provide proper support for the standard machinery units, the proposed alternative engine room structural systems will position the innerbottom structure directly under the individual unit structural stanchions. The transverse structure within the wing walls and the supporting structure on the transverse bulkheads will also be aligned with the unit framing. Parametric analyses and calculations were performed to determine the reaction loads imposed by the individual unit structures on the engine room supporting structure. The forces and moments applied at the unit/ship interface connections take into account variations in the unit structure weights, equipment and system weights, and appropriate acceleration loads.

The innerbottom structural framing system provides the basic foundation structure in way of the main engine. However, the standard machinery units must be designed to support the engine in the transverse directions by use of sway braces where required.

One benefit of unitized construction of standard machinery units is to facilitate rapid outfitting of the machinery space. Thus, the unit structure and engine room structural interface connections must be simply designed, yet able to sustain the induced forces applied to the connection. Adequate clearance in way of the unit's structural framework and attachment connections must be designed into the system to facilitate rapid installation of standard machinery units in the engine room.

## Superstructure Structural Systems

Typical ship superstructure design practice assumes that the house and stack casing are supported by the primary ship structure found within the engine room. The use of longitudinal bulkheads below the superstructure create unsupported spans within the superstructure which are relatively short, therefore, flexibility and stress are not concerns. However, unitized engine room systems allow the elimination of longitudinal bulkheads within the engine room. Therefore, superstructure must meet standard strength and vibration criteria as a standalone structure. To determine the validity of the standalone superstructure, an FEA model of the proposed structure was developed to conclude if the strength and stiffness of such a structure meets standard criteria.

The FEA model which was developed incorporated the house sides and decks as well as the transverse bulkheads at each end of the house. The geometry and scantlings of the original superstructure FEA model were based on those of a container ship as previously indicated. The superstructure and bulkheads were modeled to represent unsupported members, spanning transversely between the wing tanks, and longitudinally the length of the engine room. The decks were modeled with appropriate scantlings and plating thickness.

The self-supporting superstructure design interface with the engine room structure requires that the longitudinal wing wall structure and fore and aft transverse bulkheads be utilized to support the superstructure. Girders and bulkheads within the superstructure must be designed to interface with weather deck structure. The goal of the superstructure design is to permit load out of the engine room with machinery units, followed by erection of the entire superstructure as a single grand block, closing off the engine room compartment. The design of the superstructure connection to the main hull will facilitate rapid integration of the superstructure yet satisfy requirements for strength, rigidity and tightness.

## Results Achieved

The team concluded that innerbottom arrangements utilizing increased depth can provide stiffness comparable to the traditional arrangement. Thus, the traditional longitudinal bulkhead arrangement can be replaced by an alternative structural arrangement with a raised tank top and flat outboard.

Additionally, the team concluded that the longitudinal bulkheads within the engine room are not required to provide primary hull strength, rather they should be designed to absorb longitudinally induced loads from hull bending. With respect to build strategy, the removal of the longitudinal bulkheads facilitates installation of the standard machinery units and interface with the engine room structure. The 45,000 BHP baseline arrangement validated the feasibility of unitized engine room arrangements and reinforced the anticipated benefits.

## BUILD STRATEGY

The intent of the build strategy is to provide a standard plan for the construction of ships' engine rooms using unitized construction. The primary focus is to provide a set of parametric guidelines for the arrangement, fabrication, construction and erection of such engine rooms. These guidelines identify how stan-

dard machinery units will be fabricated and utilized across a range of ship types and sizes. Engine room system routings, which are often part of the build strategy, have been previously addressed. The build strategy establishes a benchmark for unitized engine room construction, and provides a baseline for continued improvements as measured by reduced work content, cost and cycle time.

The primary objectives of the unitized engine room construction are to:

- Allow parallel construction of the ship's machinery plant and hull structure, therefore reducing overall ship construction schedules.
- Move the majority of the work involved with building and outfitting an engine room off the ship to the more efficient ground outfitting stage.
- Allow a higher level of completion and testing of the machinery systems prior to launch.



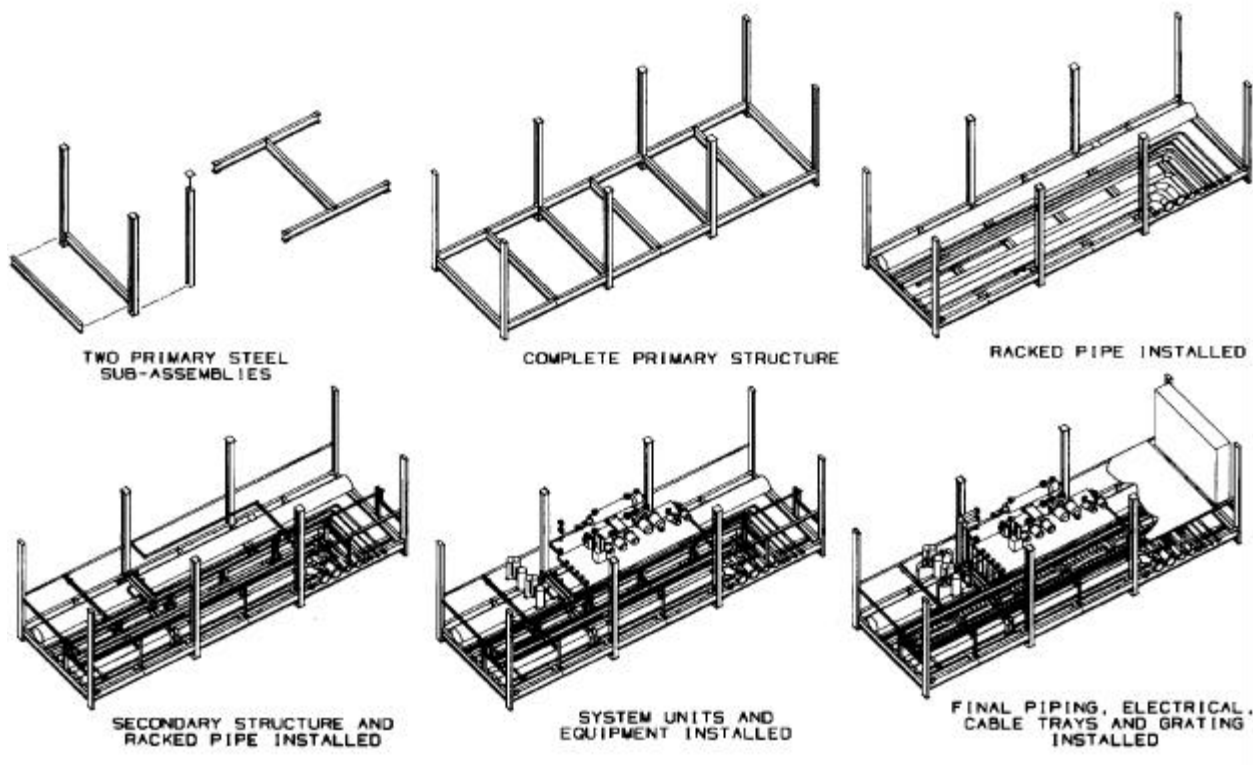


Fig. 8 Machinery Unit Assembly Process

- Give the shipbuilder the option of outsourcing part or all of the engine room construction if desired.

#### Standard Machinery Unit Assembly Process

The standard machinery unit design is based upon a standard repeating structural pattern and standard structural and system interfaces. Unit fabrication and assembly is designed for process flow lane assembly and is highly standardized.

**Structural Unit Assembly.** The structural unit design arrangement was developed to support:

- Standardization of parts, sub-assemblies, fabrication joints, and details making up the unitized structure
- Minimization of likely distortion through the assembly process
- Maximization of the use of jigs during fabrication to maintain accuracy
- Minimization of the number of pieces and joints fitted at later stages of fabrication

The structural unit assembly process makes use of two primary assemblies for construction of the standard structural unit. The pieces are all of standard length and are fabricated on a jig to maintain structural accuracy from assembly to assembly. The structural unit design can easily accept variations due to equipment weights and arrangements.

**Machinery Unit Assembly.** The standard machinery unit design arrangement was developed to support:

- Standardized arrangements, system interfaces, and construction details
- Standardized assembly sequence based upon a layered design concept with large piping and components landed using overhead cranes
- Workstation approach to unit assembly, outfit installation, and test
- Maximum outfit installation and test completion in the unit assembly stage

The machinery unit assembly process was developed to make the process as simple and efficient as possible. The unit primary steel structure is jigged during subassembly and assembly to maintain unit accuracy. Pipe is laid in rows on racks supported by the primary unit structure. Then secondary structure, additional pipe racks, and cable trays are installed prior to system unit and component installation. After main distributive systems have been installed, system units and individual equipment and auxiliaries are landed. This assembly strategy allows the units to be constructed in a layered process and allows the work packages to be scheduled in a logical and efficient sequence.

This machinery unit assembly process is shown in Fig. 8. After outfitting and testing, the standard machinery units can be further outfitted and tested at the grand unit phase.

#### Unit Hierarchy and Engine Room Construction

The machinery unit design approach utilizes a combination of ship unique pipe units, standard system units, standard machinery units, and selected individual components to complete the

assembly of the engine room. Where the shipyard has adequate lifting capacity, multiple standard units and pipe units can be combined into grand units. The hierarchy of such an engine room construction approach is illustrated in Fig. 9.

The aforementioned units may include, but not be limited to: auxiliary machinery, local and ship's distributed piping systems, foundations, decks, overheads, bulkheads, ventilation, tanks, hangers, ladders, padeyes, grating, lighting, local electrical cables, power panels, local and group controllers, and machinery automation components. Units are completed and tested to the maximum extent possible in the ground outfitting stage.

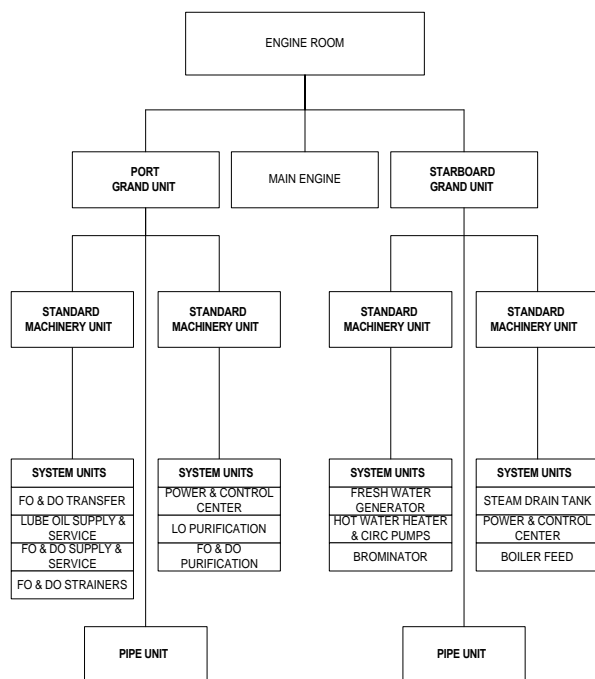


Fig. 9 Hierarchy of Engine Room Construction

Testing includes electrical cold checks and system hydrostatic testing. In some cases simulation can be run at the grand unit level to verify automated systems and interface operations. Finally, prior to erection, the units and grand units are completely painted and insulated.

The standard machinery unit engine room erection begins with the innerbottom and bottom shell blocks, engine room bulkheads, wing tanks, and box girders. The lower-level engine room units are then landed on the completed tank top. At this point engine erection will commence, followed approximately a week later by grand unit erection. The completion of engine erection and final grand unit erection will be concurrent to allow the engine room overhead blocks and house erection to be completed prior to launch.

**Accuracy Control.** Accuracy control is extremely important to the success of the unitization project. Ideally, unit steel fabrication, outfitting, grand unit assembly, and erection are done utilizing neat joints. To accomplish this level of quality control a reliable accuracy control program is imperative. To this end, the design of the standard machinery units focused on the following

key concepts:

- The unit primary steel structure is constructed of simple, repeatable subassemblies.
- The unit primary steel structure subassemblies are fabricated on assembly jigs. Weld shrinkage is consistent and well defined due to the use of standard arrangements and joint details.
- The unit primary steel structure is assembled on fabrication jigs to ensure repeatable accurate structures from unit to unit.
- The standard machinery units will be outfitted and joined at the grand unit stage using fabrication jigs throughout the process to maintain dimensional accuracy.
- The standard machinery units will be outfitted using master reference lines to prevent errors normally encountered with stackable tolerances.

**Rigging and Transportation.** One of the factors considered in the design of the standard machinery units was to ensure the ability to outsource unit construction if the shipyard desired. A detailed study of transportation including truck, rail, and barge was conducted to determine the design constraints required. This study supported the selection of structural unit sizes previously described. After evaluation, it was determined that the static, dynamic, and vibrational loads imposed by shipboard design conditions far exceed any loads that would be imposed in the transportation of units.

An additional factor considered in the structural unit design was its ability to resist racking during lifting in either a single or multiple height configuration. The structural unit design selected is highly repetitive, thus promoting the use of standard lifting frames. These frames can be made in multiple sections, each section capable of connecting to a standard machinery unit. When the units are joined side by side or end to end, multiple sections of the lifting frame can be connected and used to accomplish the lift without distortion.

## SHIP-SPECIFIC APPLICATION

The ship specific application of the standard machinery unit concept was included as the final project task of the ERAM portion of the Navy's Mid-Term Sealift Technology Development Program. The ERAM project team, assembled in 1995, was tasked with developing and applying an Integrated Product and Process Development (IPPD) design approach to concurrent engineering for the specific application of engine room arrangement, conceptual design, and integrated 3-D product modeling.

## ERAM Team and Team Objectives

The ERAM team consisted of representatives from participating U.S. shipyards, foreign shipyards, owner/operators, engine manufacturers, government agencies, design agents and support personnel. The team is cross functional, co-located, and has been professionally trained. The ERAM team objectives were as follows:

- Provide a forum for U.S. shipbuilders to present views and needs for product and process design.
- Within 12 months develop a process for marine industry use to design internationally competitive commercial ships.

- Within 24-months demonstrate the process by designing four “World Class” engine room arrangements.
- Achieve customer-focus and buy-in of product design (4 engine room arrangements).
- Achieve U.S. shipbuilding industry-focus and buy-in of process design.
- Establish baseline commercial ship engine room designs for evaluation of future government initiated change.
- Document both the product and process design with rationale for use and future refinement by other users.

### Project Approach

After NASSCO had developed the standard machinery unit concept a workshop was presented to the ERAM team and steering committee to provide developmental information on the para-

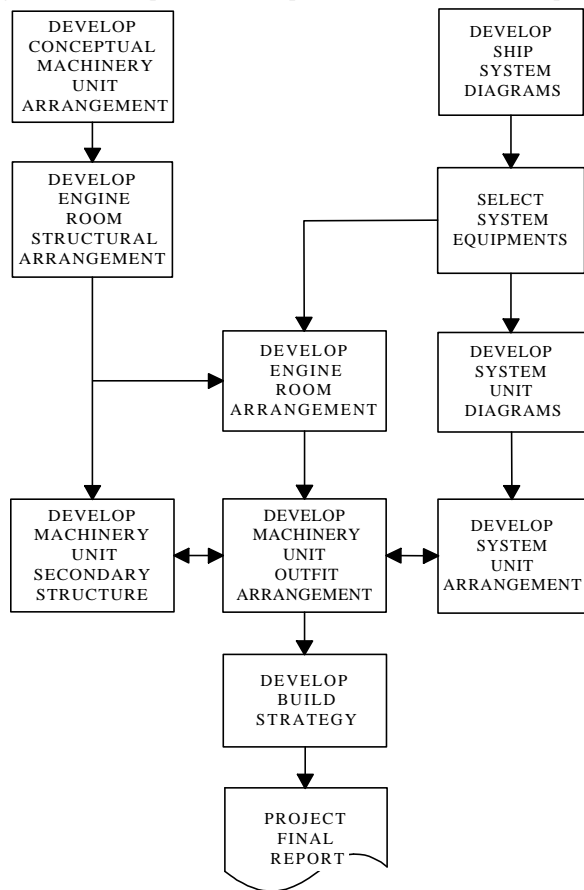


Fig. 10 Standard Machinery Unit Design Process

metric approach and an understanding as to how these solutions were to be applied. The approach that was chosen by the ERAM team consisted of selecting a previous iteration from the ERAM project, Slow Speed Diesel #1 (SSD #1), as the baseline design for applying the standard machinery unit concept. This new iteration would become the Slow Speed Diesel #3 (SSD #3) design. The results were then evaluated in the business evaluation task.

### Slow Speed Diesel #3 Characteristics

The vessel characteristics of the SSD #3 were derived from the MARAD PD337 enhanced cargo ship design, a combination RO/RO container ship. They are as follows:

- Length overall - 200m (656 ft)
- Molded beam - 32.2m (105.62 ft)
- Molded depth - 18.0m (59 ft)
- Design draft - 9.15m (30 ft)
- Design displacement - 36,700 tons
- Ship service speed - 20 knots
- Main engine - MAN B&W 7S70MC slow speed diesel, 22500 BHP at 91rpm

### Design Process

The standard machinery unit design application process is shown in Fig. 10. This high-level process flow chart shows how to effectively integrate the standard machinery unit concept in the design process. However, it should be noted that this process is a concurrent engineering approach, and that several process steps are being applied in parallel.

**SSD #3 Fixed Parameters.** Several of the existing parameters from the SSD #1 design were retained to ensure focus of the SSD #3 design iteration on the standard machinery concept application. This process ensured that the business evaluation was an accurate and useful tool. These fixed parameters included: equipment selection, a centerline stack, heat load requirements, high and low seachests with a sea pipe, and the selection of submerged main engine lube oil pumps. A standard machinery unit size of 3.6m x 3.6m x 4.0m (12ft x 12ft x 13ft) was selected based on a metric equivalent of the parametric approach recommended for this specific vessel.

**Structural Interface.** Once a conceptual standard machinery unit arrangement had been identified that would optimize the engine room configuration, an approach to integrate the ship's structure with that of the machinery unit's was agreed upon. The rationale behind this approach was to derive a structural system with a stiffness value equal to the original SSD #1 design. The removal of several internal tanks along with longitudinal bulkheads in way of the machinery units made for a very soft hull structure. Several options were evaluated, including the “coupling” of machinery units at 5m (16.4 ft) from centerline port and starboard to increase the stiffness. However, the final solution was the selection of a partial span longitudinal bulkhead at 5m (16.4 ft) off centerline, port and starboard. This part span bulkhead provided the necessary stiffness while still allowing an open architecture for easy loading of machinery units, particularly at the forward end of the engine room.

**Systems Design.** Development of ship specific system diagrams used SSD #1 as a baseline. The parametric approach was applied, including lessons learned from previous ERAM project designs. This ship specific solution included owner/operator options and addressed a life cycle cost of fifteen years. Comparison tables were created to document system deviations from the SSD #1 baseline and the standard machinery unit concept. The team

determined that any deviation from the parametric system approach would demonstrate the design flexibility of the approach. System equipment was selected from the SSD #1 base line, and new equipment was included as necessary to support the developed systems.

**Engine Room Arrangement.** The recommended approach was to apply a family of templates to develop an engine room arrangement. These templates gave the ERAM team a common starting point to develop three alternative options. The template family also identified, at the highest level: Access, equipment

removal, and distributive system routes, thus simplifying the development of the three options. Analysis of the three options and the parametric templates identified improvements that could be made to the template family, the analysis tools, and ultimately the selected arrangement itself. The engine room arrangement specific to this ship application is shown in Fig. 11.

A key feature of the template application was the identification of locations of the engine control room, workshops, and store-rooms. These locations revealed a large emphasis on engine room arrangement acceptability from a potential owner/operator standpoint. Location of system specific machinery units was generally

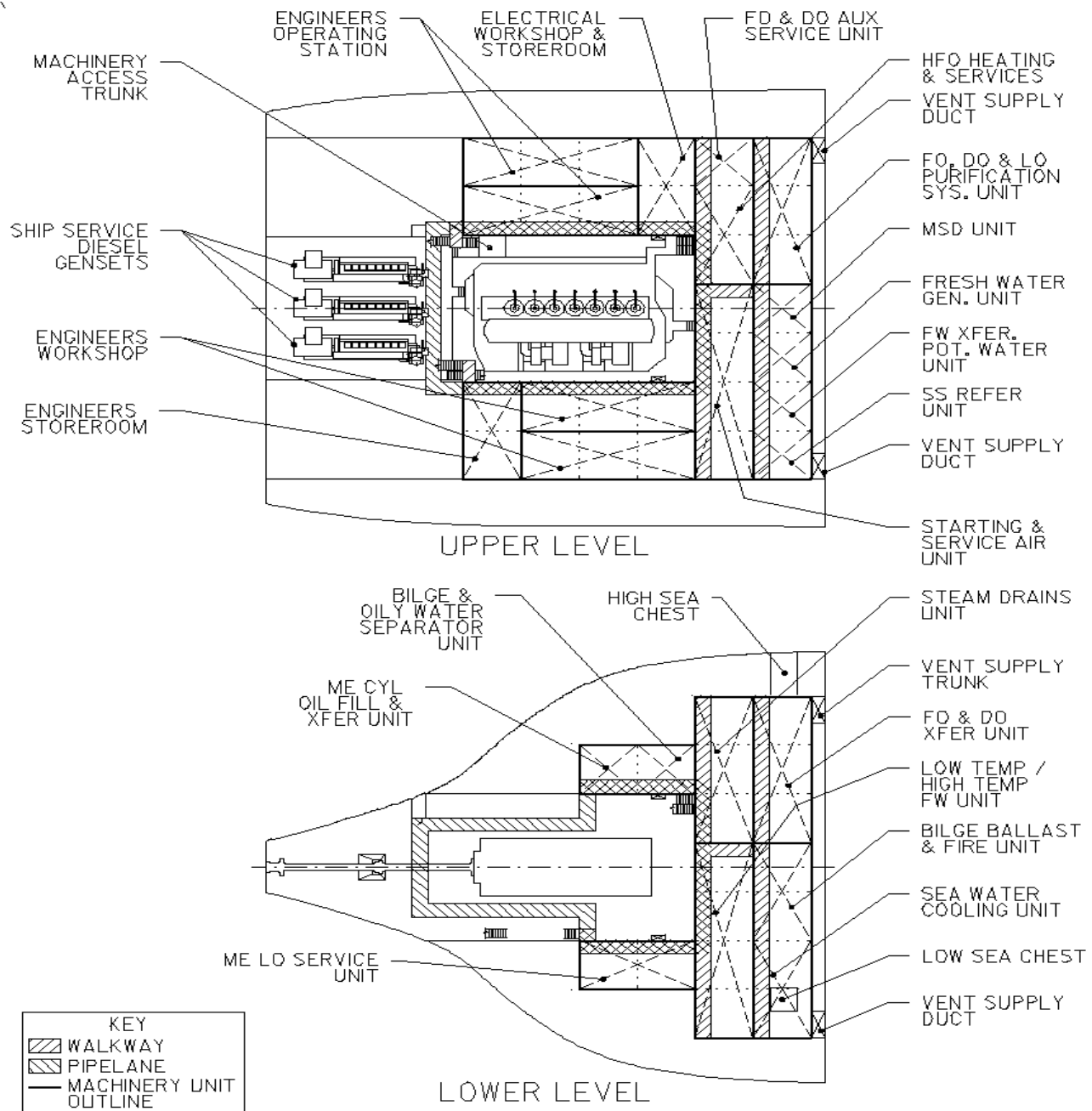


Fig. 11 Engine Room Arrangement SSD#3

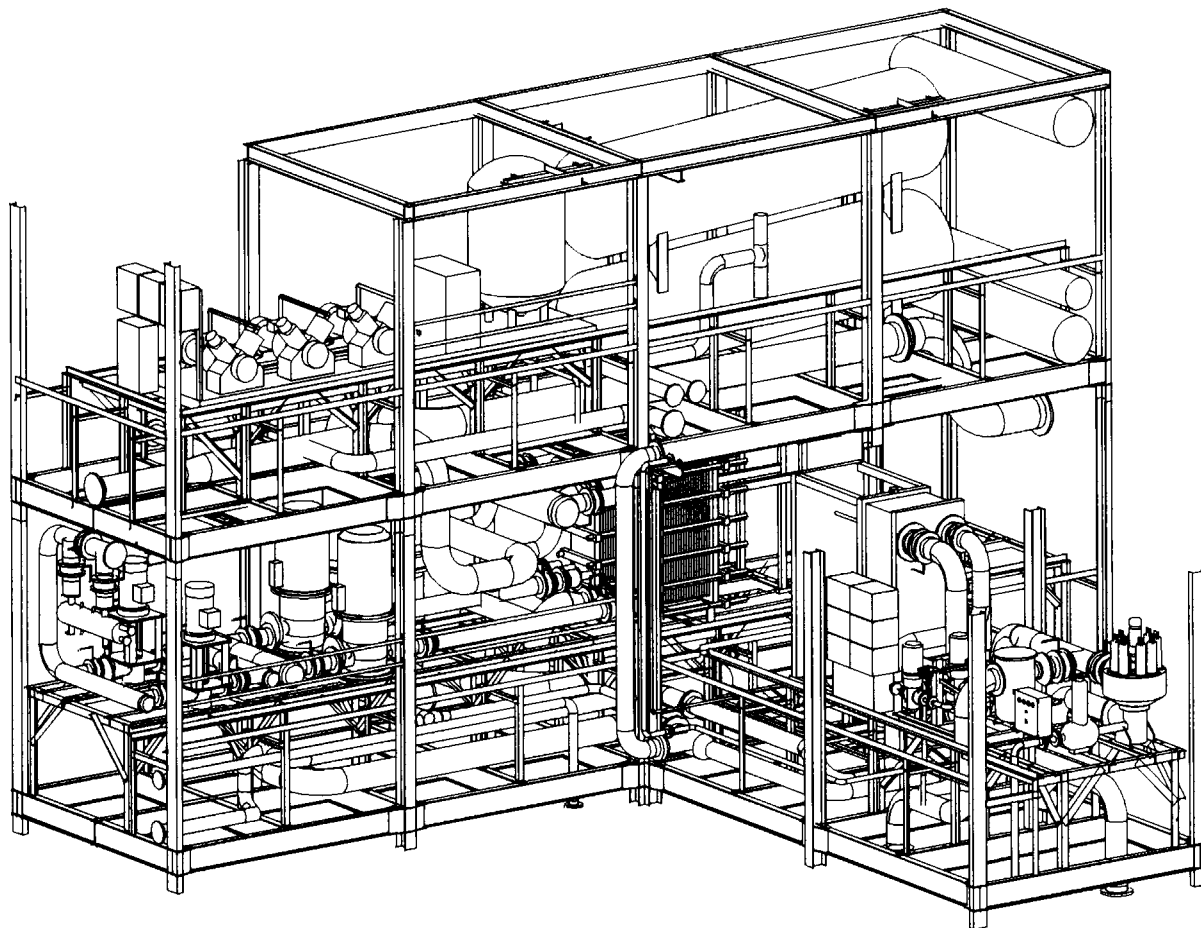


Fig. 12 Three Standard Machinery Units on SSD#3

easily agreed upon. Vent duct location to serve the engine room also created some concern as to the impact on potential cargo space, therefore, the forward vent ducts were relocated inside the machinery space.

**Machinery Unit Design.** The first step in the machinery unit design process was to develop system unit diagrams. These system units would in turn be located on the standard machinery units. System unit arrangements were then developed from these system unit diagrams. The use of vendor supplied system units was maximized where possible, however, some system units were designed in-house.

After personnel access arrangements were developed, the location of equipment within the machinery units was optimized. This included consideration of: Human factors engineering, simplified piping arrangements, and accommodation of maintenance and removal envelopes. A pipeline density study was performed to identify machinery unit through piping. Machinery unit secondary structure was developed and integrated to support system units and personal access walkways. The area beneath these walkways has been designated as the primary location for cableways and through piping. Segregating secondary structure from unit primary structure yielded a design that could be divorced for a parametric solution to equipment foundations. However, analy-

sis for exceptionally heavy equipment indicated that in some cases additional primary structure is needed in the transverse direction due to the loading from roll accelerations. Additionally, structure was added to the machinery units located on the upper level to cap the top of the unit and enable complete pre-outfitting prior to loading onboard.

Five standard machinery units were selected to be fully detailed by the ERAM team. They were: lube oil service unit, fresh water cooling unit, compressed air unit, steam drains unit, and seawater unit. A 3-D model of three of these machinery units is illustrated in Fig. 12. These units were selected to provide detailed proof of the concept in specific key areas and to compliment NASSCO's earlier product development.

**Build Strategy.** Three grand units were identified, center-line, port, and starboard to be pre-assembled and installed in the engine room. The large seawater main is intended to be installed at grand unit stage of construction. A total of twenty three system units are contained within the seventeen standard machinery units. These standard machinery units consists of either a two, three or four bay standard structural unit. The team determined that by increasing the levels of outfitting installation and testing, and maximizing pre-outfitting of electrical power and automation systems, considerable cost and

schedule savings were to be realized. The parametric approach and ship specific application to the SSD #3 design also identified considerable schedule savings from contract award to start of fabrication, where material lead time is on the critical path.

## Lessons Learned

**Process.** The parametric approach to the machinery unitization concept provided a “jump start” for the ERAM team to commence the SSD #3 design iteration. This systematic approach provided a technically sound foundation upon which the ERAM team built. The experience yielded positive feedback to both the ERAM team and the NASSCO machinery unit design team.

Parts of the developed process became iterative, specifically the detailed development of machinery unit design. Application of this concept allows packaging of both the system architecture and the design effort itself into manageable tasks.

The IPPD process that the ERAM team developed and practiced allowed the concept to develop at an accelerated rate. Applying a parametric approach to machinery unitization allowed a higher level of concurrent engineering than any of the previous engine room design iterations.

**Product.** Because an owner/operator had been included as the voice of the customer from the ERAM project inception, satisfying the customer had become a very important part of the ERAM project. Locations of control rooms and store rooms within an engine room may be representative of the types of problems potential shipyards could encounter when trying to implement the parametric approach from a series of standard templates with a specific customer requirement.

Improvements to the parametric family of templates that were identified during this design iteration have been included in the complete template range to retain commonality throughout the parametric approach.

Within the workshops and stores areas traditional deck plating contained within the machinery units was considered the best solution to allow customer flexibility in relocating equipment. This also provides containment of fluids within areas with traditional deck drains.

Specific owner/operator concerns over operation and maintenance were considered during the SSD #3 design. These concerns were mainly the ingress and egress of equipment and personnel, complicated by the addition of several vertical stanchions between the machinery unit areas. Vertical stanchions within the engine control room and workshop areas are not required on the upper levels, and may be removed to minimize this effect.

In general, owner/operator participation in the ERAM SSD #3 design process was very valuable and it identified several improvements to both the concept and the specific design.

## BUSINESS ASSESSMENT

As part of the Standard Machinery Unit development project, a business assessment of potential cost and schedule impacts was accomplished by three U.S. shipyards (Avondale, Bath Iron Works, and NASSCO) assisted by the ERAM Team. In support of this analysis, the ERAM Team provided a detailed comparison of design weights and footage's. A summary of these design metrics is shown in Fig. 13. This data shows a significant reduction

Metric	SSD #1	SSD #3
Steel		
ER Structure (Tons)	1,680	1,641
ER Unit/FDN (Tons)	64	151
Total	1,744	1,792
Pipe		
Spooled (Ft.)	10,334	9,629
Non-Spooled (Ft.)	7,750	7,221
Total	18,054	16,850
Vent		
Spooled (Ft.)	915	1,010
Cable		
Power (Ft.)	36,631	32,968
Automation (Ft.)	21,178	19,060
Lighting (Ft.)	10,000	9,000

Fig. 13 Design Metrics

in pipe and cable footage, along with a small structural weight increase on SSD #3 relative to SSD #1. In addition, the participants were provided a complete design package for each of the ships being evaluated.

As part of the assessment, the three shipyards developed an analysis of potential advanced outfit metrics as shown in Fig. 14. This analysis shows a marked increase in on-unit completion levels in all categories, with a corresponding decrease in onboard work scope for SSD #3 relative to SSD #1. It must be recognized that the ability to achieve these metrics will be dependent upon the shipyard's ability to effectively implement the unitization concept through design and planning, and to develop an integrated test program.

With respect to the maturity of the standard machinery unit design concept, the three shipyards agreed that the cost and schedule assessment would be developed on the assumption that the concept had been fully developed and that an initial family of parametric standards was available.

## Cost Assessment

In developing the cost assessment, two shipyards estimated only the portion of the engine room designed with standard machinery units, while the third shipyard estimated the complete engine room. A synthesis of their estimates of the potential cost improvement for SSD #3 relative to SSD #1 is shown in Fig. 15. While the shipyards anticipate that the initial development of parametric design guidelines may represent an increase in design manhour cost in the short term, they all agreed that there were potential savings in the order of 50-60% in engineering and planning, 35-50% in production, and 15-20% in material procurement over a series of several ship contracts.

Metric	SSD #1			SSD #3		
	On Unit	On Board	On Block	On Unit	On Board	On Block
Mechanical Equipment (%)	65	25	10	85	10	5
Electrical Equipment (%)	10	75	15	85	10	5
Pipe (%)	15	70	15	70	25	5
Ventilation (%)	0	90	10	70	25	5
Cable						
Power (%)	15	30	55	70	5	25
Automation (%)	15	30	55	75	5	20
Lighting (%)	0	80	20	75	10	15
Test (%)	5	30	65	60	5	35

Fig. 14 Advanced Outfit Metrics

The principle factors supporting these savings in cost include:

- System design and arrangement standards
- Standard unit structure, arrangements and details
- Standard vendor equipment
- Reduced design work content
- Ability to subcontract unit design/production
- Flow lane construction of machinery units
- Reduced onboard installation and test work scope
- Reduced onboard construction and test schedule
- Reduced product and process variation

#### Schedule Assessment

In assessing the potential schedule improvement, an overall design and construction activity schedule was developed for conventional design and construction, SSD #1, and for a ship designed and constructed with standard machinery units, SSD #3.

This evaluation was reviewed by the three shipyards and found to be representative. This analysis is summarized in Fig. 16. The comparison shows a lead ship schedule of 19 months for SSD #3 with unitized construction vs. a schedule of 24 months for SSD #1 with conventional construction. It should be noted that individual ship construction schedules using standard machinery unit technology will have to be developed on a case by case basis considering the ship type, size, and shipyard capacity available. The principle factors supporting these reductions in cycle time include:

- Reduced system and detail design time
- Reduced auxiliary equipment procurement time
- Reduced machinery unit assembly time
- Parallel steel and outfit construction leading to later installation of engine room outfit
- Increased preoutfit installation and test levels
- Reduced onboard construction and test schedule
- Reduced product and process variation

Cost	SSD #1 Baseline	Standard Machinery Unit Design		
		1st Ship	4th Ship	8th Ship
Engineering	100 %	80 - 100 %	50 - 65 %	40 - 50 %
Design	100 %	80 - 100 %	50 - 65 %	40 - 50 %
Planning	100 %	80 - 100 %	50 - 65 %	40 - 50 %
Production	100 %	80 - 90 %	65 - 75 %	50 - 65 %
Material *	100 %	90 - 95 %	85 - 90 %	80 - 85 %

\* Material excludes Main Engine

Fig. 15 Projected Cost Comparison

Schedule Interval	SSD #1	SSD #3
CA - SF	11	8
SF - K	3	3
K - L	6	5
L - D	4	3
TOTAL (months)	24	19

Fig. 16 Projected Schedule Comparison

## SUMMARY

A parametrically derived family of large, fully integrated standard machinery units that are applicable over a range of ship types and installed horsepower has been developed. Although the project described focused on commercial ship machinery spaces using slow speed diesel power plants from 10,000 to 50,000 BHP, the approach is applicable with modifications to other ship types, power plants, and power ranges.

This system includes a family of integrated standard machinery units that replace conventional engine room flats and distributed machinery systems and components. The design guide developed as part of this project includes a hierarchy of standard units, the selection of standard unit sizes and interfaces, parametric design guidelines for system design, engine room arrangement and engine room structural design, and machinery unit structural and outfitting design. The approach described incorporates best practices as observed in “World Class” marine and U.S. land-based industrial plant design and construction. The design selected is considered superior to other marine applications observed, and is fully supportive of the original project objectives.

The standard machinery unit system has been demonstrated on a ship-specific engine room design and the business impact has been assessed by three U.S. shipyards. The results of the business assessment with respect to overall cost and schedule improvement are shown in Fig. 15 and 16. The principle design, material procurement, and production productivity improvement factors are summarized in Fig. 17. While additional development is required to support full implementation, the work to date demonstrates that the approach is both technically feasible and that its application to shipbuilding will result in strategic reductions in total program cost and schedule.

Design	Material Procurement	Production
<ul style="list-style-type: none"> <li>• System design standards</li> <li>• Arrangement standards</li> <li>• Equipment standards</li> <li>• Machinery unit standards</li> <li>• Parallel Steel and Outfit Design</li> <li>• Reduced work content <ul style="list-style-type: none"> <li>⇒ system architecture</li> <li>⇒ arrangements</li> <li>⇒ unit structure</li> </ul> </li> <li>• Reduced product variation</li> </ul>	<ul style="list-style-type: none"> <li>• Equipment standards</li> <li>• Reduced work content</li> <li>• Simplified unit structure</li> <li>• Reduced product variation</li> </ul>	<ul style="list-style-type: none"> <li>• Reduced work content</li> <li>• Work-station construction of engine room outfit</li> <li>• Parallel steel and outfit construction</li> <li>• Ability to sub-contract unit design and/or construction</li> <li>• Reduced onboard installation and test</li> <li>• Reduced product and process variation</li> </ul>

Fig. 17 Standard Machinery Unit Productivity Factors



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